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HIGH VISCOSITY LIQUID PAYLOAD YAWSONDE DATA FOR SMALL LAUNCH YAWS

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June 1980

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Eight projectiles filled with high viscosity liquid payloads were tested at Wallops Island, Virginia, on 16 October 1978. These shells were instrumented with fuze-configured yawsondes and were filled with liquid payloads whose viscosities were three to five orders of magnitude larger than that of water. Unstable flights occurred for launch yaws as small as 2.5 degrees for the higher viscosity liquid payloads. This type of flight instability cannot be predicted by available liquid-filled projectile theories and represents a hazard to new payload concepts that may employ such liquids.

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I. INTRODUCTION

Eight projectiles filled with highly viscous liquid payloads were flight tested at Wallops Island, Virginia, on 16 October 1978. Yawsonde data were obtained on seven of the rounds, and the data show that high viscosity liquid payloads can produce projectile instabilities at initial yaw levels as small as 2.5 degrees. The resulting instability is characterized by a rapid increase in yaw and a dramatic reduction in spin. This coupling between the yaw and spin is typical for a payload induced instability.

II. BACKGROUND

A new and potentially dangerous flight instability has been observed for rapidly rotating, highly viscous liquid payloads.[1] Detailed flight data have been obtained via yawsonde and radar measurements and these data are in qualitative agreement with a laboratory spin fixture[2]. A series of 155mm projectiles were fitted with steel cylindrical canisters (interior dimensions: 50.8 cm in length and 11.75 cm in diameter) and launched at nominal spin rates of 100 rps. All canisters were filled to 100 percent with liquids whose kinematic viscosity were three to six orders of magnitude larger than that of water. Induced launch yaws of 10 degrees produced unstable flights for a band of viscosities centered at 2×10^5 centistokes (cs)[3].

The unpredictable behavior of liquid-carrying projectiles has provided shell designers with many surprises and frustrations. The classical liquid-filled instability was first documented with respect to bulk-filled liquid payloads whose viscosities did not vary appreciably from that of water[4]. An important non-dimensional grouping for all phenomena in rotating liquids is the Ekman number ($E=\nu/a^2p$, where ν is

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1. *W.P. D'Amico and M.C. Miller, "Flight Instability Produced by a Rapidly Spinning, Highly Viscous Liquid," Journal of Spacecraft and Rockets, Vol. 16, No. 1, January-February 1979, p. 62.*

2. *M.C. Miller, "Flight Instability Test Fixture for Non-Rigid Payloads," Special Publication ARCSL-SP-79005, Chemical Systems Laboratory, USAARRADCOM, Aberdeen Proving Ground, MD, January 1979. AD B034708L.*

3. *W.P. D'Amico, W.H. Clay, and A. Mark, "Diagnostic Tests for Wick-Type Payloads and High Viscosity Liquids," BRL Memorandum Report No. ARBRL-MR-02913, April 1979. AD A072812.*

4. *Engineering Design Handbook, Liquid-Filled Projectile Design, AMCP 706-165, April 1969.*

the kinematic viscosity, a is the radius of the cylinder, and p is the spin of the cylinder). The Ekman number compares the relative magnitude of viscous to Coriolis forces. For water-like projectile payloads, E is commonly as small as 10^{-6}. For the unstable payloads within this report, E is much larger, say, 10^{-1}. The classical liquid-filled shell instability ($E \ll 1$) results from a matching of a frequency of the wave motion within the liquid (not a sloshing motion since the centrifugal forces are much larger than any body forces such as gravity or drag, i.e., the Froude number $ap^2/g \gg 1$) and the fast frequency of the projectile motion. A resonant condition is established, and a liquid-induced couple acts to overturn the projectile. This explanation and an inviscid theory were offered by Stewartson.[5] Subsequently, Wedemeyer derived a displacement thickness correction to account for viscosity[6]. The possibility of a wave-type instability for $E \sim 1$ cannot be ruled out, but the viscous corrections of Wedemeyer are subject to the normal type boundary layer assumptions and cannot be realistically applied. On the other hand, interesting work has been accomplished by Vanyo, Lu, and Weyant in the measurement of energy dissipation in precessing and spinning spheres with E as large as unity.[7] Hence, a combination of wave motion and viscous dissipation could be central to the explanation of this new projectile instability. A preliminary analysis by Vaughn constructs an azimuthal velocity profile with a center of rotation that is not coincident with the geometric center of the cylinder. Although this velocity does not produce a net torque on the cylinder, integral methods to calculate the angular momentum of the total projectile/liquid system produce surprising agreement with data by Miller.[8] A detailed and accurate description of the destabilizing mechanism for $10^{-1} < E < 10^{-3}$ is not available.

5. K. Stewartson, *"On the Stability of a Spinning Top Containing Liquid"*, *Journal of Fluid Mechanics 5, Part 4 (1959).*

6. E.H. Wedemeyer, *"Dynamics of Liquid-Filled Shell. Theory of Viscous Corrections to Stewartson's Stability Problem," Ballistic Research Laboratories Report No. 1287, 1965. AD 472474.*

7. J.P. Vanyo, V.C. Lu, and T.F. Weyant, *"Dimensionless Energy Dissipation for Precessional Flows in the Region of Re=1", Journal of Applied Mechanics, December 1975, pp 881.*

8. H.R. Vaughn, *"Flight Dynamic Instabilities of Fluid-Filled Projectiles", Sandia Laboratories Report No. 78-0999, June 1978.*

III. TEST RESULTS

A. Hardware and Test Equipment

The 155mm projectiles used for this test were M687 shell fitted with single piece steel canisters. A one-fourth caliber boattail was employed. All projectiles were instrumented with BRL fuze-configured yawsondes.[9] Yawsonde data are presented in the form of solar angle and spin histories. SIGMA N is the complement of the solar angle, that is the angle between a vector drawn from the center of gravity of the projectile to the sun and a vector aligned with the spin axis of the projectile. Spin data from the yawsonde are presented in terms of the derivative of the Eulerian roll angle of the projectile, PHI DOT. The true spin of the projectile is only approximated by PHI DOT, but this approximation is very good as long as the angular motion of the projectile and the spin do not vary rapidly. A properly reduced PHI DOT requires the use of data from both optical sensors of a yawsonde, and such methods are outlined by Murphy[10]. When the methods of Reference 10 are not applied, the spin data are labeled PHI DOT (RAW). A spin history derived from raw yawsonde pulses produces a smooth curve with small oscillations superimposed. These small oscillations are a result of the yawing motion. The mean of such oscillations should be regarded as the actual spin of the projectile.

Tests were conducted as the NASA Launch Facility, Wallops Island, Virginia. A time-position radar and a break-wire time-zero system were operated by Wallops Island personnel, while the gun, a muzzle chronograph, and a launch area telemetry site were manned by BRL personnel. Main base telemetry from Wallops Station (approximately ten miles from the launch site) also monitored the yawsondes, but only the data from the mobile site were reduced.

B. Yawsonde Data

A round-by-round summary of the test is provided in Table 1, while projectile physical characteristics are found in Table 2. Figures 1-3 show the yawsonde data for E1-9540. This corn syrup-loaded projectile was launched with an FMA* of 4.5 degrees and was unstable. The slow

9. *W.H. Mermagen and W.H. Clay, "The Design of a Second Generation Yawsonde," Ballistic Research Laboratories Memorandum Report No. 2368, April 1974. AD 780064.*

10. *C.H. Murphy, "Effect of Large High-Frequency Angular Motion of a Shell on the Analysis of Its Yawsonde Records," Ballistic Research Laboratories Memorandum Report No. 2581, February 1976. AD B0094210.*

* *The first maximum amplitude (FMA) is half of the first recorded peak-to-peak excursion of SIGMA N.*

TABLE 1. Round-By-Round Summary[1]

Round Number	BRL Number	Muzzle Velocity (m/s)	Launch Condition	Payload Type	FMA[7] (degrees)	Comments
E1-9540	1585	333.4	Mass Induced[2]	Corn Syrup[4]	4.5	Unstable - good data
E1-9541	1586	339.3	Mass Induced[2]	Corn Syrup[4]	---	Unstable - no data
E1-9542	1587	331.6	Normal	Corn Syrup[4]	2.5	Unstable - good data
E1-9543	1588	325.9	Normal	Corn Syrup[4]	2.5	Unstable - good data
E1-9544	1550	329.3	Yaw Induced[3]	Glycerol[5]	13.5	Stable - good data
E1-9545	1589	326.6	Yaw Induced[3]	Glycerol[5]	16.5	Stable - good data
E1-9546	1591	-----	Yaw Induced[3]	Silicon Oil[6]	14.5	Stable - good data
E1-9547	1592	-----	Yaw Induced[3]	Silicon Oil[6]	14.0	Stable - good data

[1]All projectiles were conditioned to 25.5°C and fired from an M185 tube on a fixed mount at a quadrant elevation of 30° with a standard M4A1 powder weight for charge 4. Charges were at ambient temperature.

[2]A standard muzzle brake was used, but the projectile canisters were modified to accept a 640 gm off-set mass as a yaw induction technique (see Reference 11).

[3]Modified muzzle brake with 13cm high side plates.

[4]Kinematic viscosity of 1.7×10^5 cs.

[5]Kinematic viscosity of 1×10^3 cs.

[6]Kinematic viscosity of 1×10^3 cs.

[7]The first maximum amplitude (FMA) is half of the first recorded peak-to-peak excursion of SIGMA N.

11. *C. H. Murphy, "Yaw Induction by Mass Asymmetry,"* *Journal of Spacecraft and Rockets, Vol. 14, pp. 511-512, August 1977. (See also BRL MR 2669, August 1976, AD B013362l).*

TABLE 2. Projectile Physical Characteristics

Round Number	Mass (kg)	Center of gravity (m from base)	Moments of Inertia Axial (kg.m^2)	Moments of Inertia Transverse (kg.m^2)	Shot Mass (kg)
E1-9540	38.92	0.328	0.163	1.611	46.70
E1-9541	38.99	0.329	0.164	1.613	46.75
E1-9542	39.02	0.328	0.164	1.613	46.80
E1-9543	39.08	0.329	0.164	1.616	46.84
E1-9544	39.18	0.328	0.165	1.617	46.02
E1-9545	38.97	0.328	0.164	1.614	45.81
E1-9546	39.09	0.329	0.164	1.617	44.41
E1-9547	39.14	0.329	0.165	1.618	44.47

yaw frequency damped while the unsteady fast mode became dominant by a flight time of 5 seconds. A coning motion with a half-angle of nearly 50 degrees and a rapid despin occurred at 17 seconds (Figures 1 and 3). Figure 2 shows an expanded view of the initial angular motion. and it is evident that the fast mode motion is unstable at shot exit. Useable yawsonde data were not obtained for E1-9541 due to a shift in the transmitter frequency and/or a weak on-board battery. This projectile was tracked by radar and achieved only 80 percent of its expected range. Figures 4-6 show the yawsonde data for E1-9542. This corn syrup-loaded projectile had an FMA of 2.5 degrees and suffered the same type of instability as E1-9540, although dramatic spin losses occurred a little later in the flight (20 seconds as opposed to 17 seconds). Figure 5 shows the angular motion subsequent to shot exit, and, as before, the fast yawing motion was unstable at launch. Figures 7-9 show the yawsonde data for E1-9543. The behavior of this corn syrup-loaded shell was quite similar to that of the previous two projectiles, with the fast mode motion unstable from shot exit (Figure 8).

The next four projectiles were filled with glycerol or silicon oil. The silicon oil was selected to have a kinematic viscosity approximately equal to that of glycerol. These projectiles were tested to demonstrate that a reduction in the liquid payload viscosity of two orders of magnitude would produce stable flights and to investigate liquid despin/large yaw effects at shot exit. Two different liquids were used to preclude nonlinear flow characteristics of any single liquid dominating the observed data. All four of these projectiles were stable with FMA levels of approximately 15 degrees. Figures 10-12 show the yawsonde data for E1-9544, which was filled with glycerol. Although amplitude modulation of the PHI DOT (RAW) data complicates the shape of the spin history, Figure 12 does indicate a rapid decay of spin at shot exit. Figures 13-15 show the yawsonde data for E1-9545, which was also loaded with glycerol. An expanded spin history also shows a rapid despin at shot exit. Figures 16-18 show the yawsonde data for E1-9546, while Figures 19-21 show the yawsonde data for E1-9547. Both of these rounds were filled with silicon oil, and both exhibited rapid spin decays at shot exit (Figures 18 and 21).

IV. DISCUSSION

Raw yawsonde data can be further processed to yield interesting results. As an example, the data from E1-9542 will be examined. The raw SIGMA N data can be digitally filtered to produce an amplitude history for only the fast mode. Figure 22 shows the results of such a digital band-pass filter for E1-9542. The amplitude of the envelope in Figure 22 can be directly obtained by complex demodulation and is presented in Figure 23 on a linear amplitude scale or in Figure 24 on a logarithmic scale. Note that some noise still exists within the data in Figure 22, noteably at 9 and 11 seconds, and this noise produces

spurious results in the complex demodulation routine (Figures 23 and 24). Figure 23, however, clearly indicates that the fast mode is unstable from shot exit, but Figure 24 does not portray a constant exponential growth rate.

A quantitative examination of the spin histories for the glycerol and silicon oil rounds would be required to establish whether the data follow expected decay rates. The computation of the angular momentum history of the projectile/liquid system using methods developed by Mark [12] could be used to identify the time to liquid spin-up thereby determining if the liquid followed a laminar type spin-up mechanism at shot exit or whether the rapid despin follows a non-laminar phenomenon.[13] These projectiles had viscosities that were within the range of the data of Reference 13, but slightly larger yaw levels were achieved.

V. CONCLUSION

Projectiles were filled with highly viscous liquids, launched at very small yaw levels, and were unstable at shot exit producing rapid growths in yaw and decreases in spin. The flight instability cannot be explained by available liquid-filled projectile theories and represents a potential hazard to new payload concepts if high viscosity fluids are employed.

VI. ACKNOWLEDGEMENT

The authors are indebted to Dr. Richard Whiting who coded the digital filter, complex demodulation, and graphic display routines that were used within this report.

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12. A. Mark, *"Measurements of Angular Momentum Transfer in Liquid-Filled Projectiles," USA Armament Research and Development Command, Ballistic Research Laboratory Technical Report No. ARBRL-TR-02119, November 1977. AD A051056.*

13. W.P. D'Amico, W.H. Clay, and A. Mark, *"Yawsonde Data for M687-Type Projectiles with Application to Rapid Spin Decay and Stewartson-Type Spin-Up Instabilities," US Army Ballistic Research Laboratory Report in publication.*

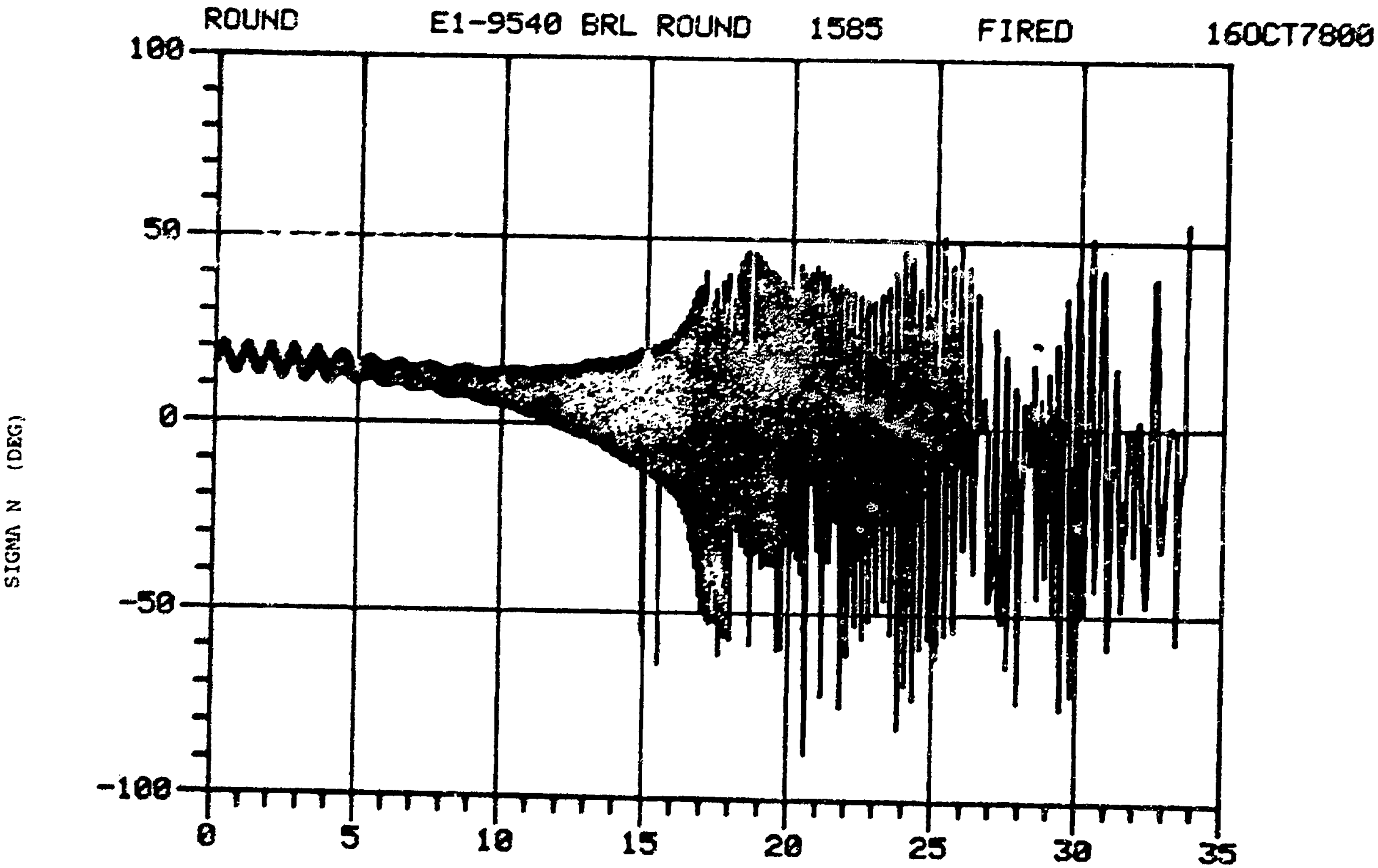

Figure 1. Sigma N versus Time for E1-9540.

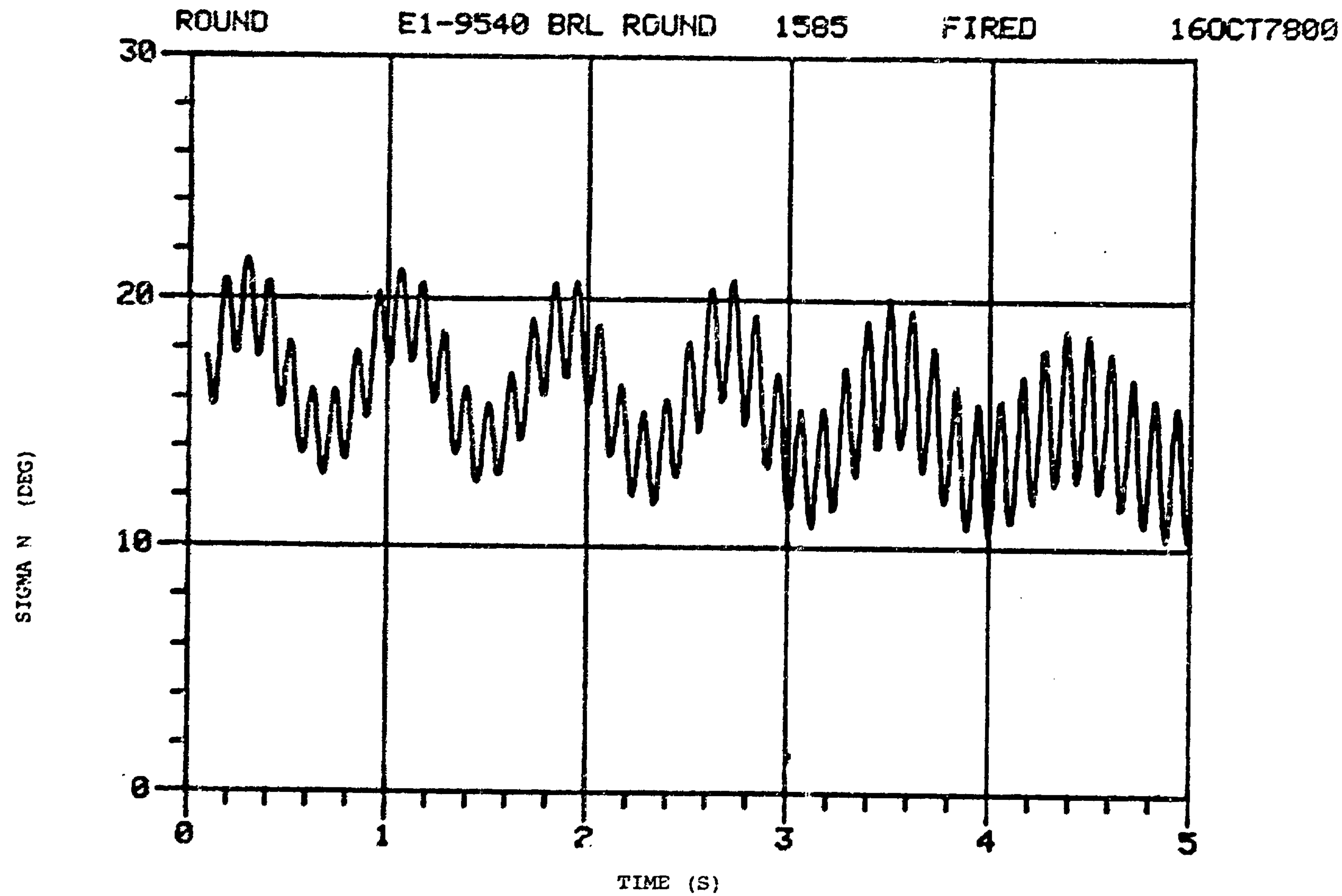

Figure 2. Sigma N versus Time for E1-9540 (Zero to 5s).

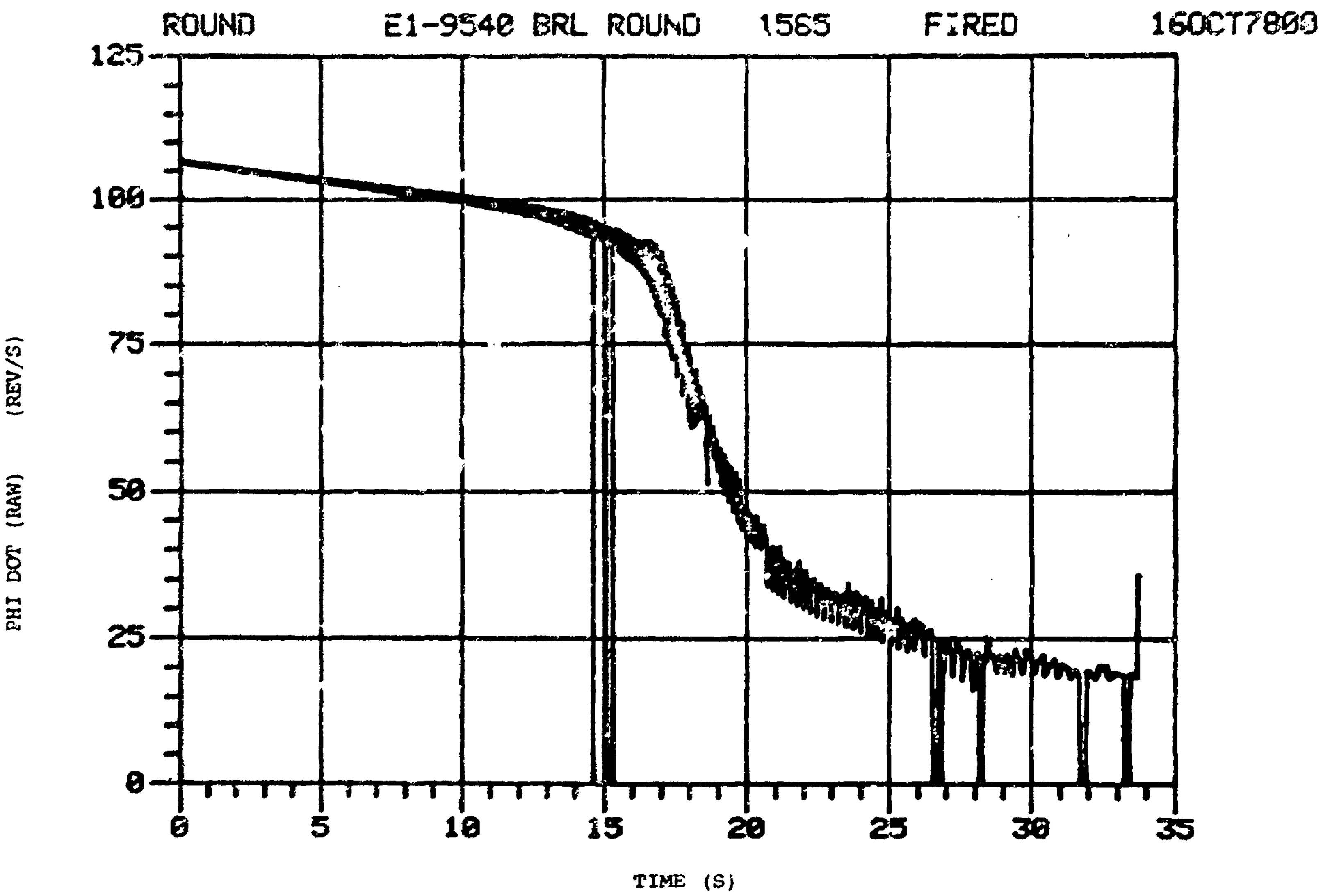

Figure 3. Phi Dot (Raw) versus Time for E1-9540.

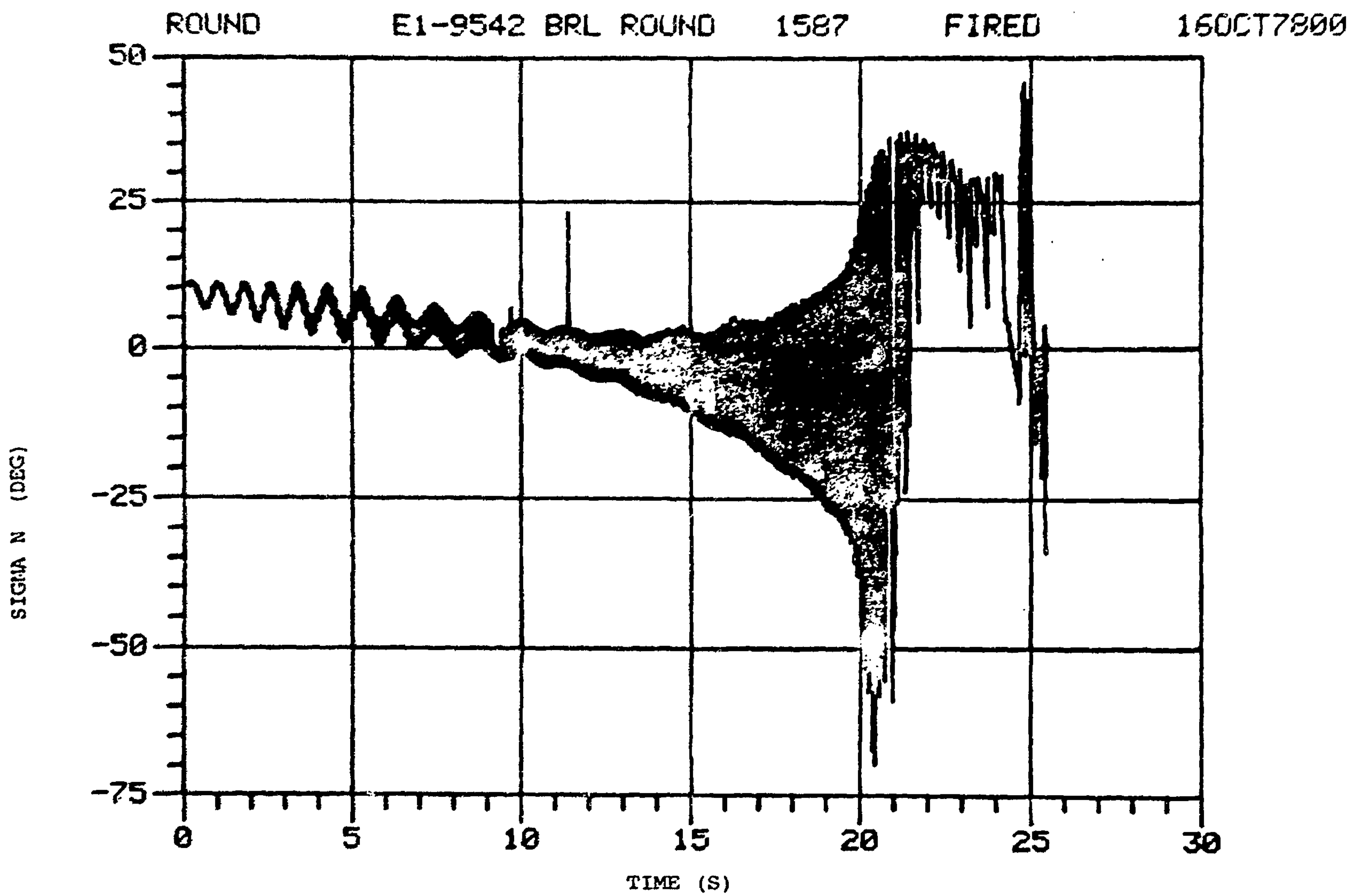

Figure 4. Sigma N versus Time for El-9542.

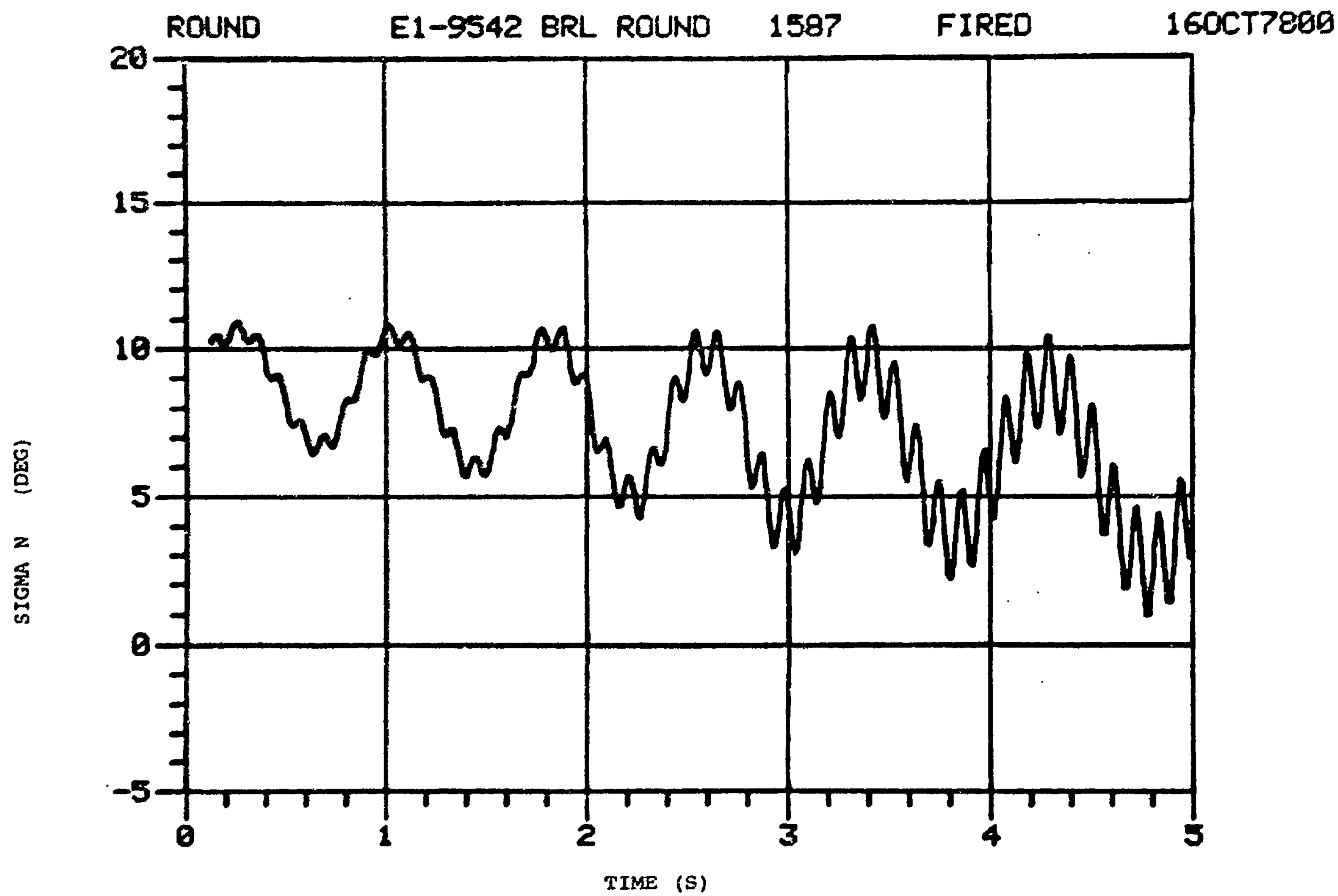

Figure 5. Sigma N versus Time for E1-9542 (Zero to 5s)

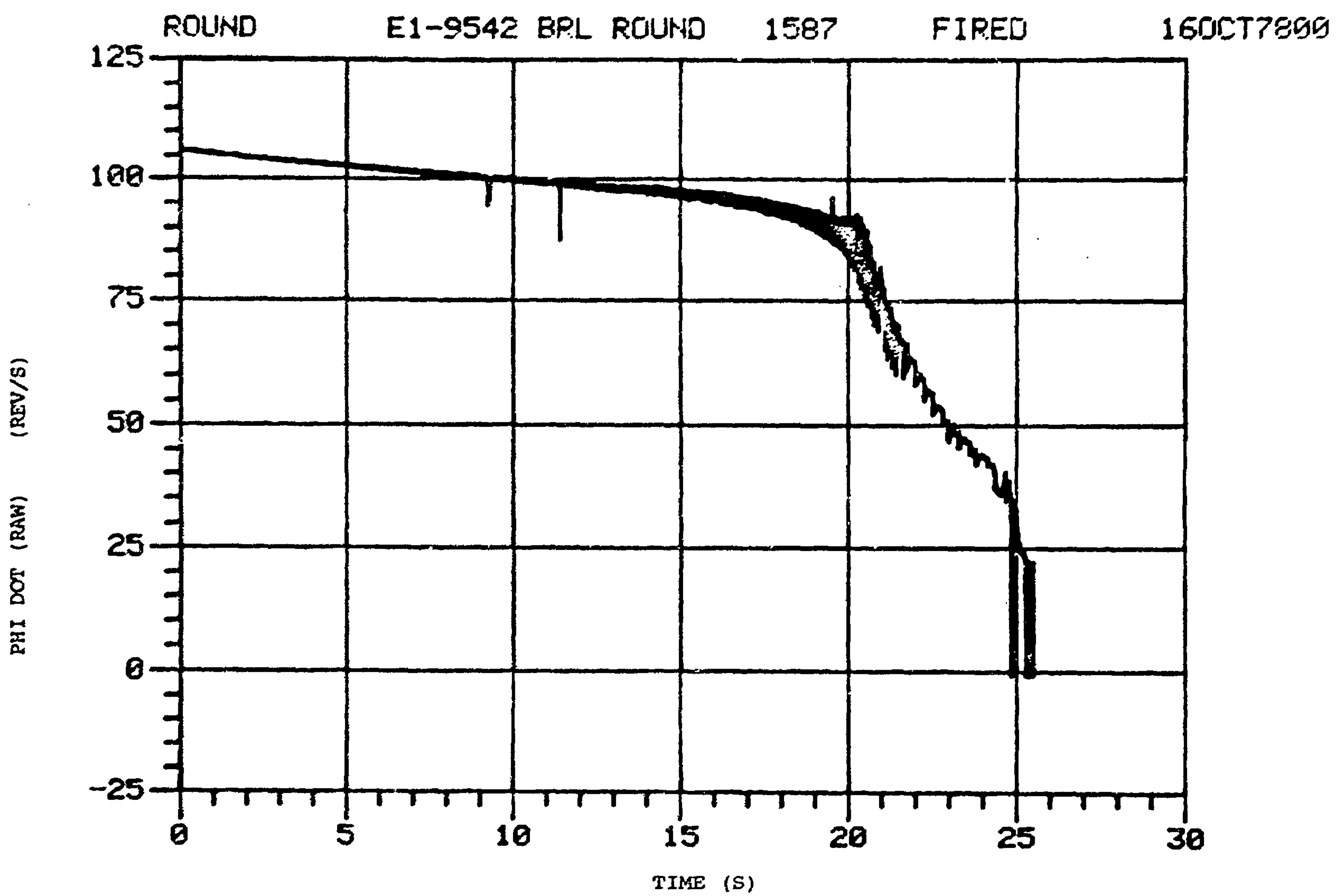

Figure 6. Phi Dot (Raw) versus Time for E1-9542.

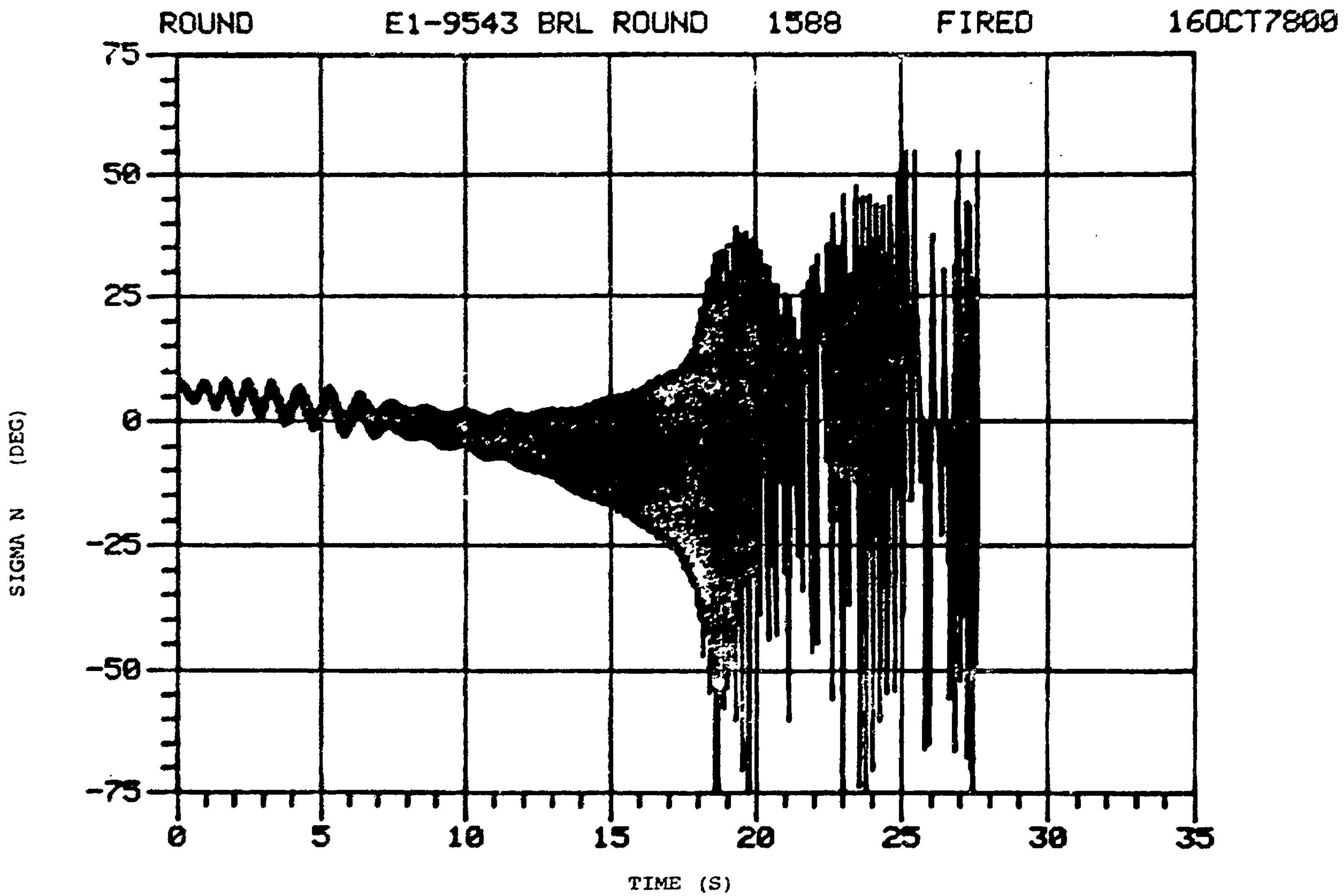

Figure 7. Sigma N versus Time for E1-9543.

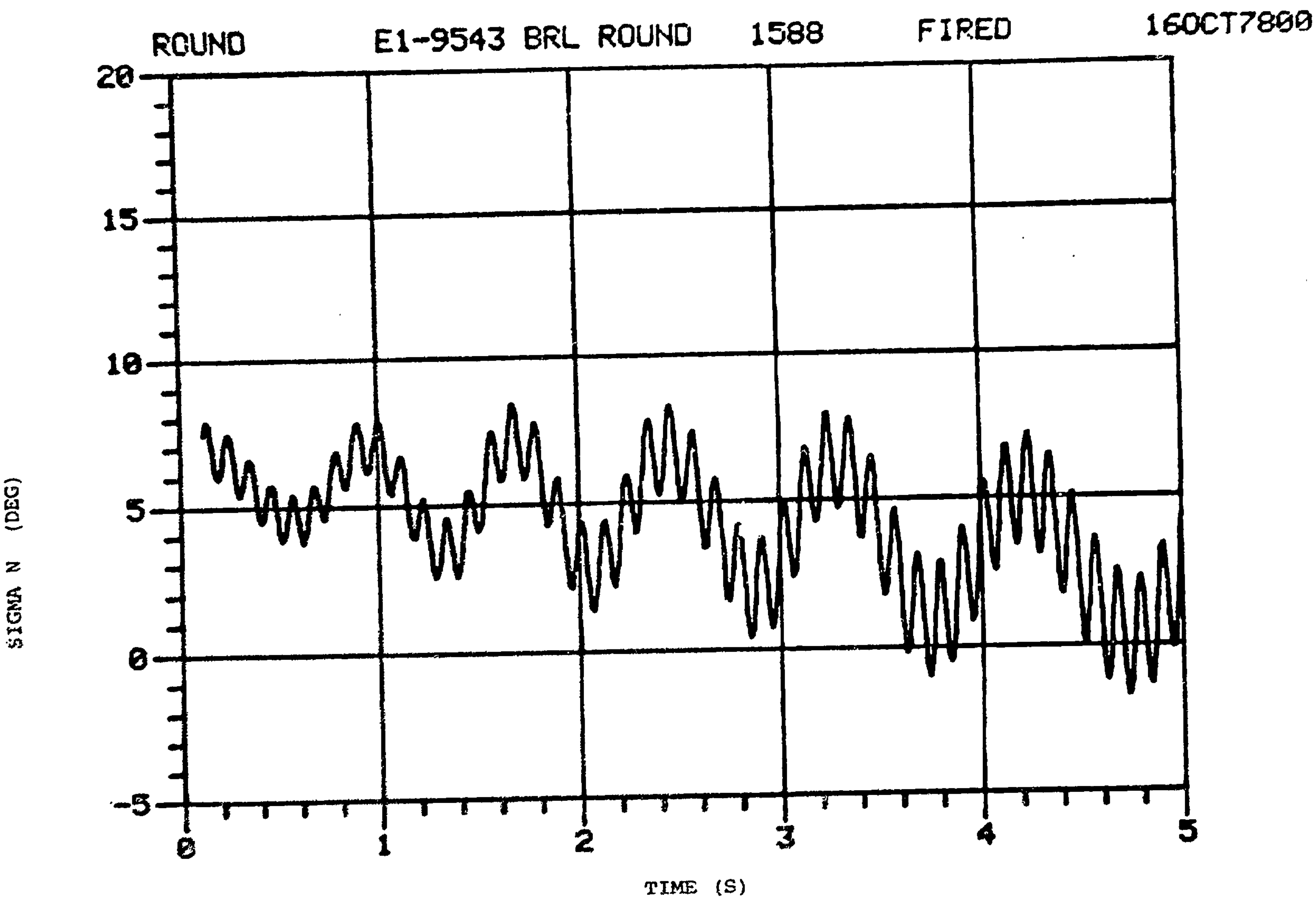

Figure 8. Sigma N versus Time for E1-9543 (Zero to 5s).

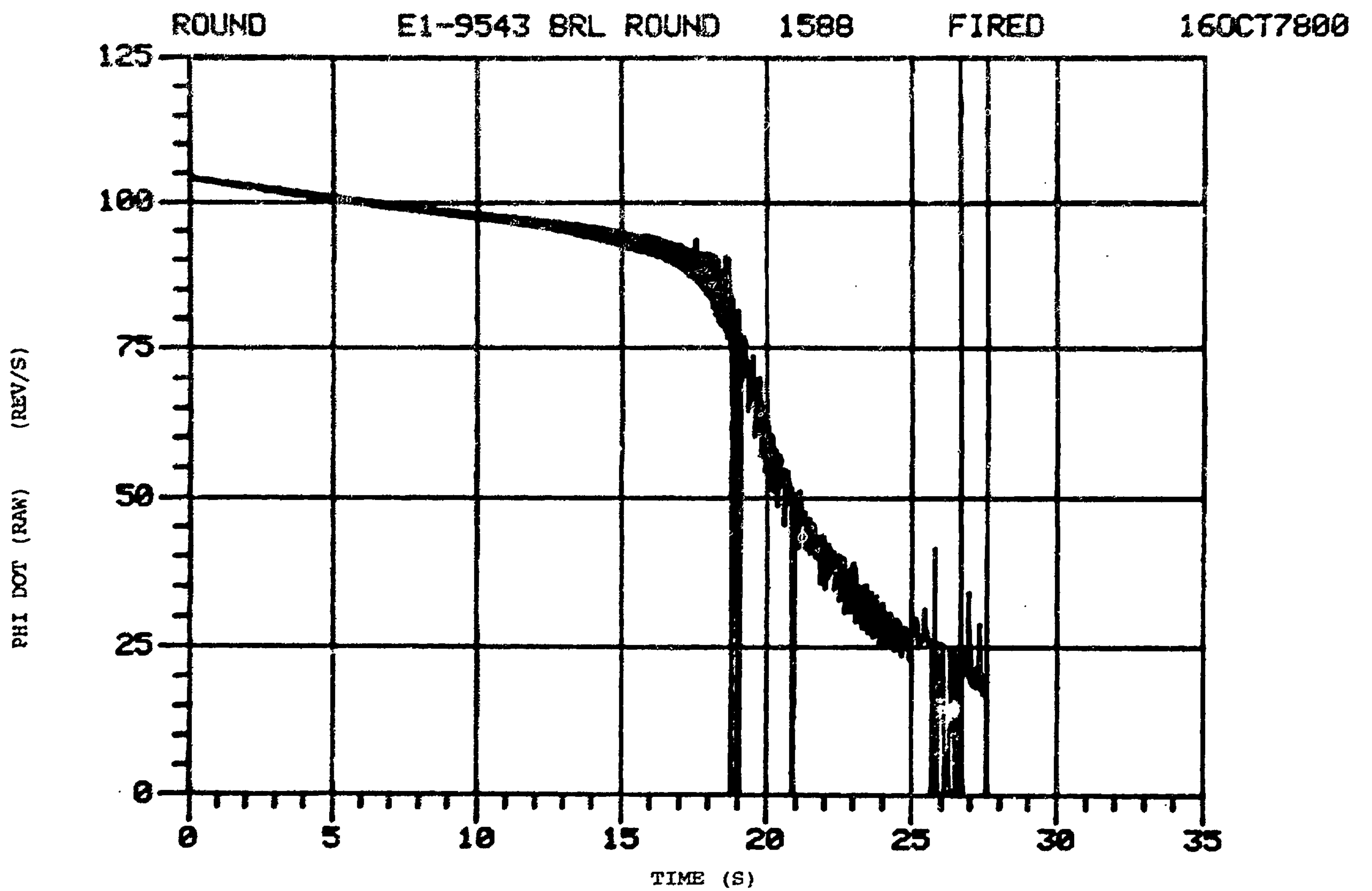

Figure 9. Phi Dot (Raw) versus Time for E1-9543.

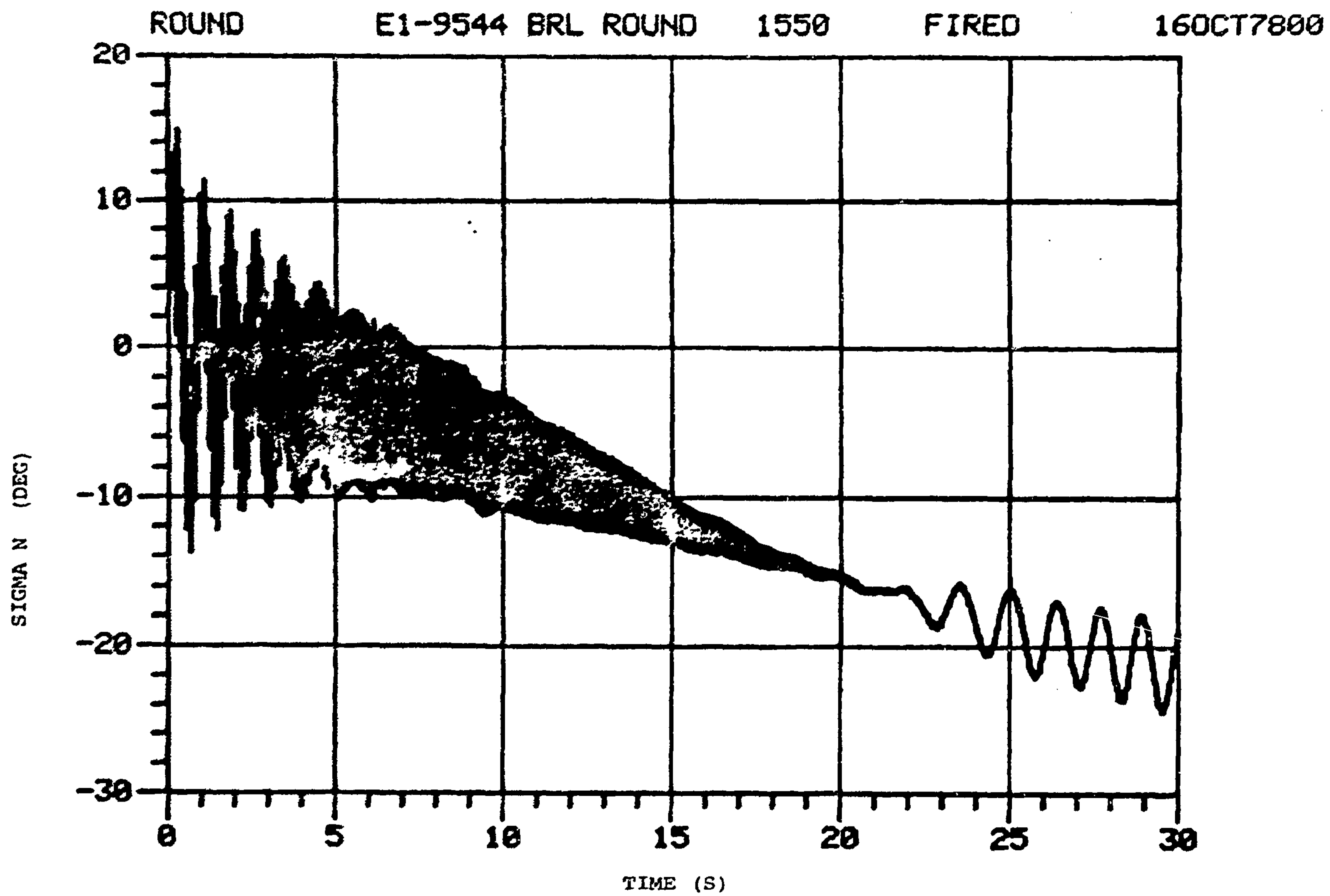

Figure 10. Sigma N versus Time for El-9544.

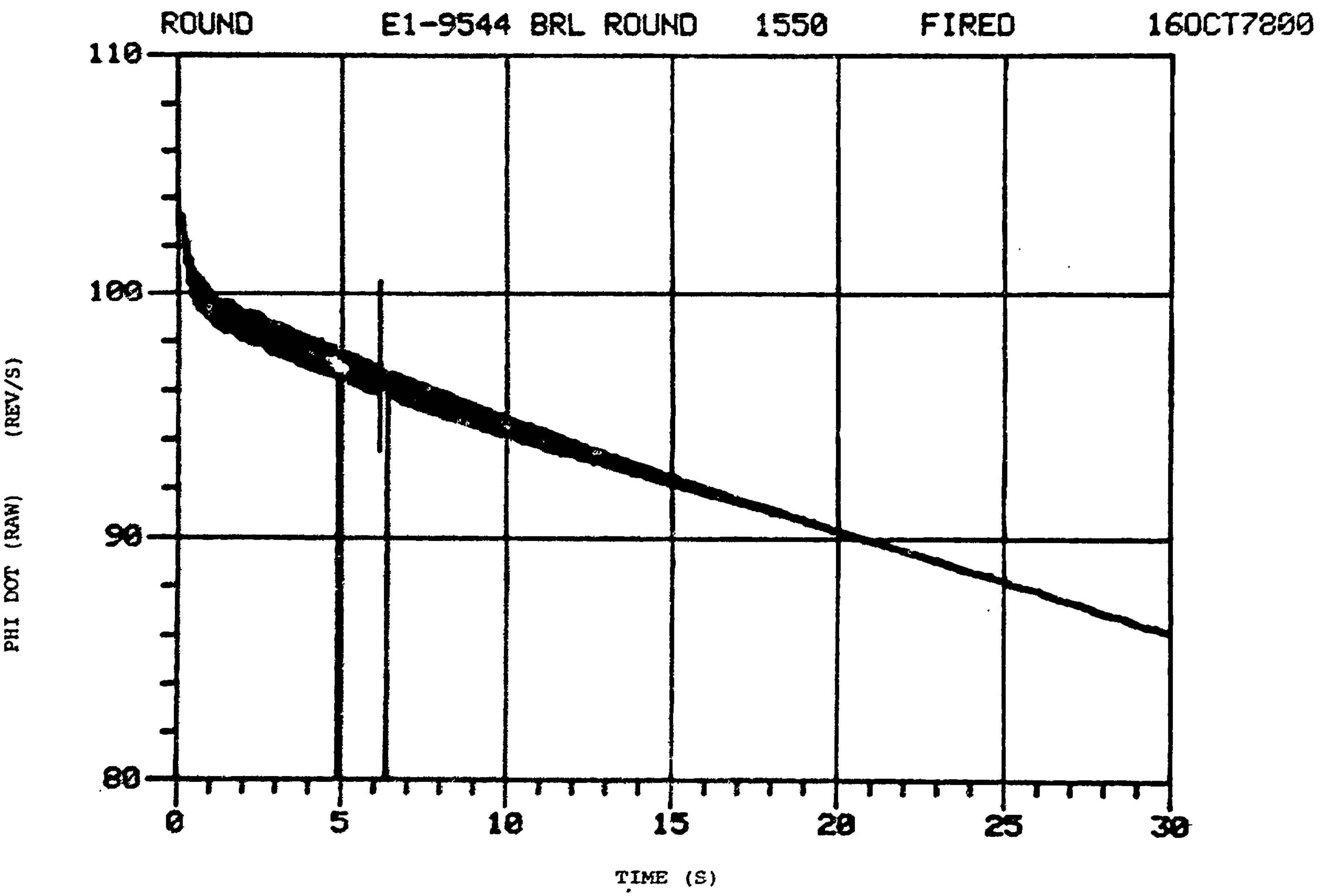

Figure 11. Phi Dot (Raw) versus Time for E1-9544.

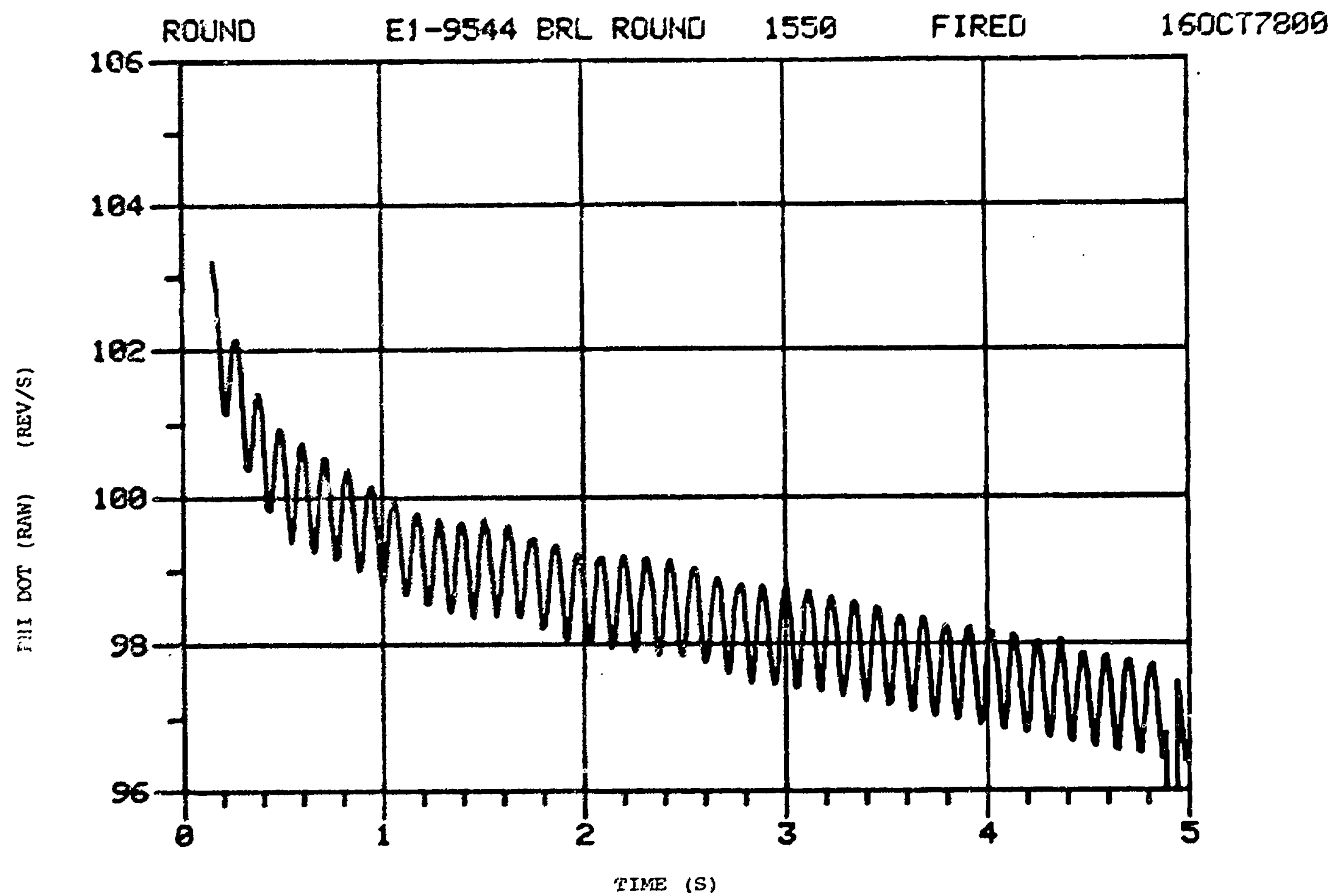

Figure 12. Phi Dot (Raw) versus Time for E1-9544. (Zero to 5s)

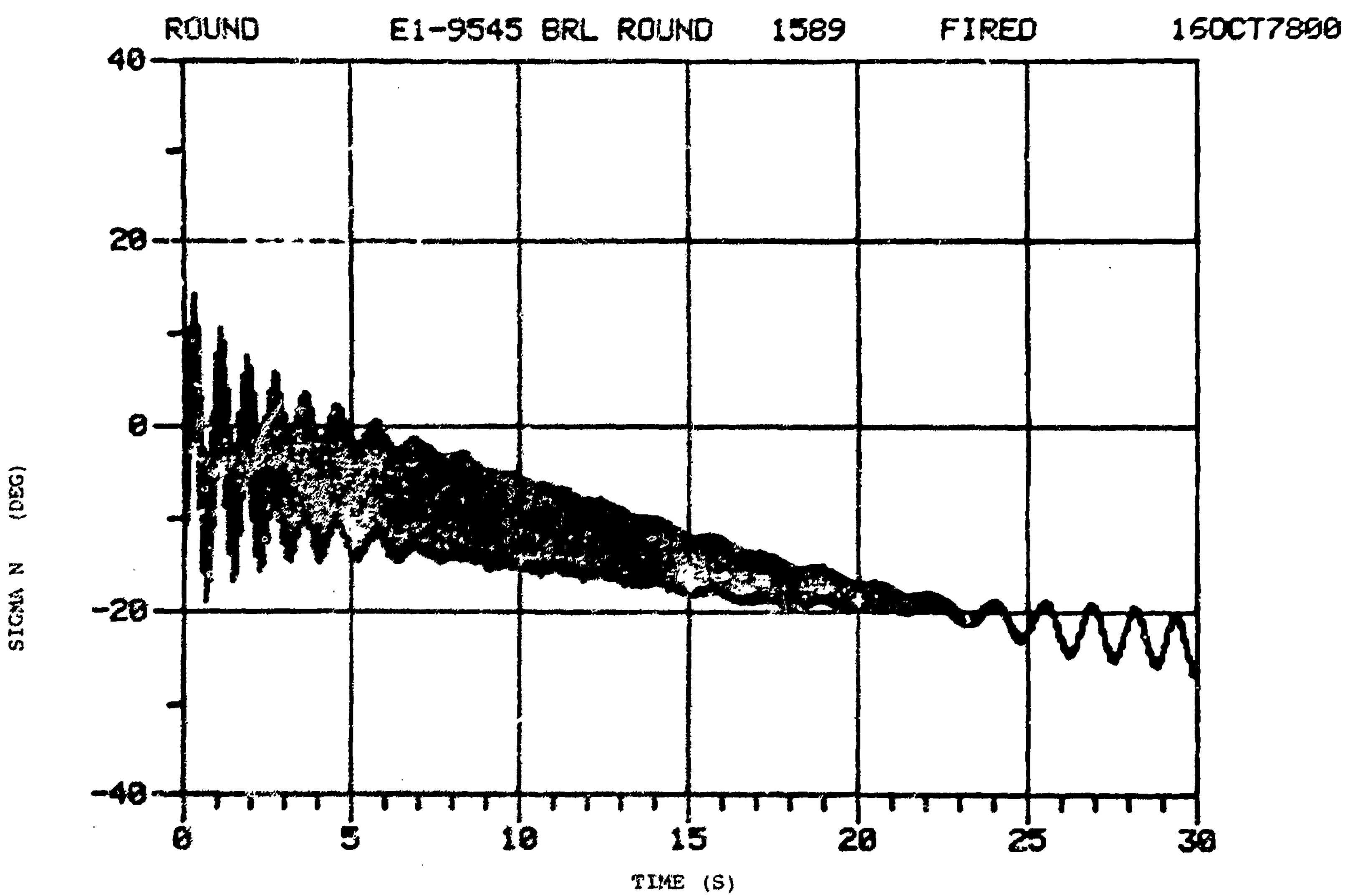

Figure 13. Sigma N versus Time for E1-9545.

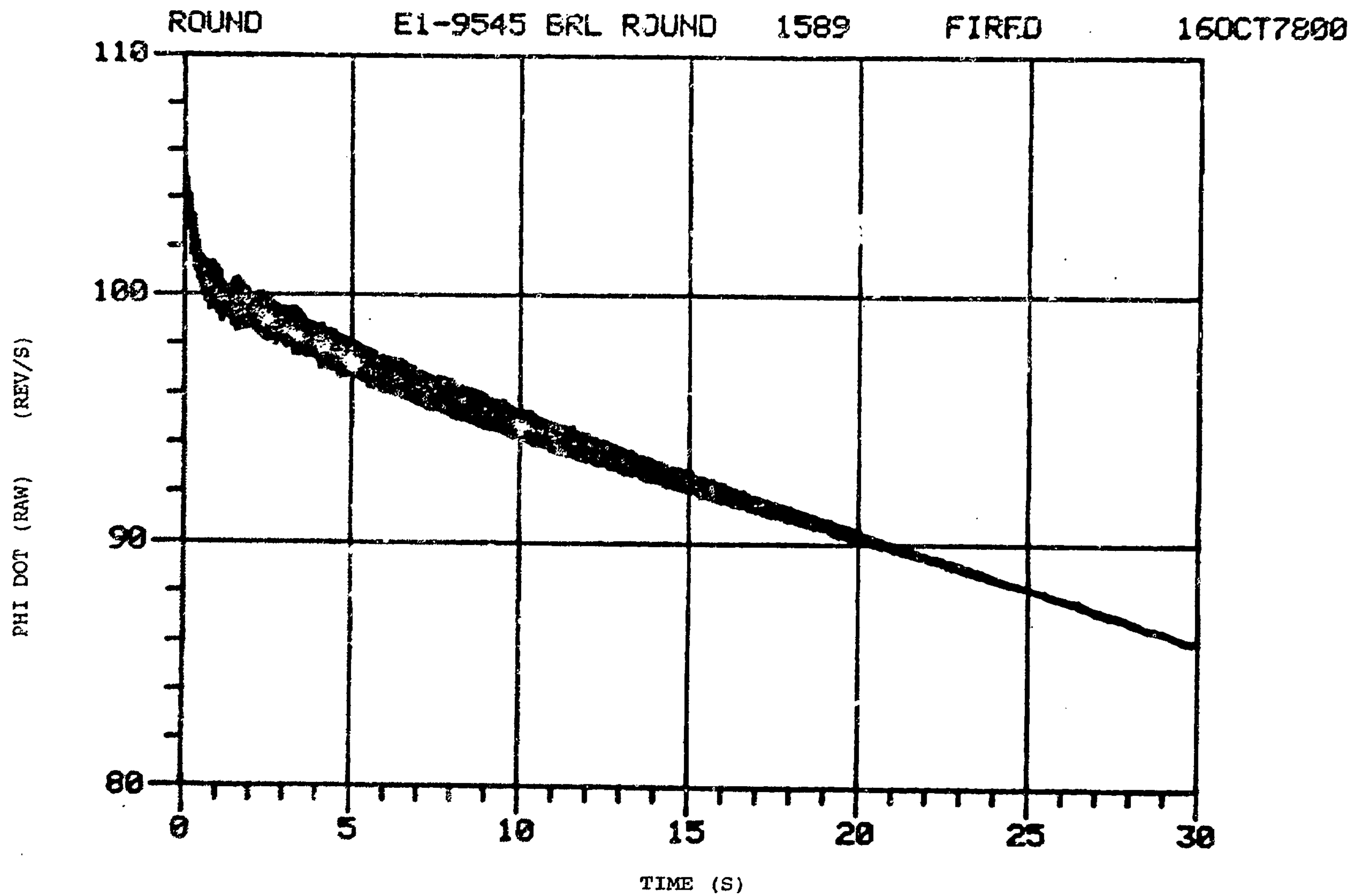

Figure 14. Phi Dot (Raw) versus Time for E1-9545.

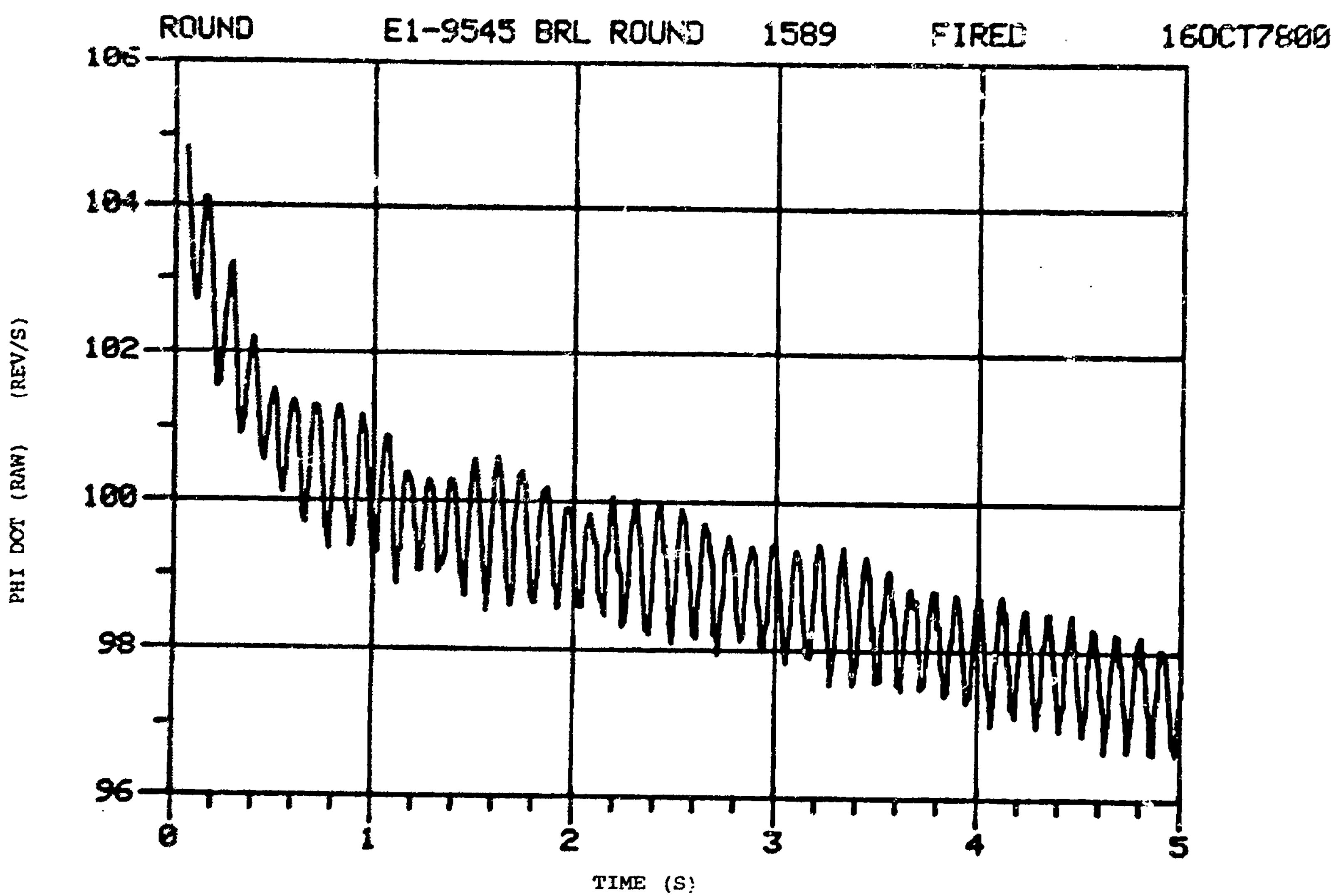

Figure 15. Phi Dot (Raw) versus Time for E1-9545 (Zero to 5s).

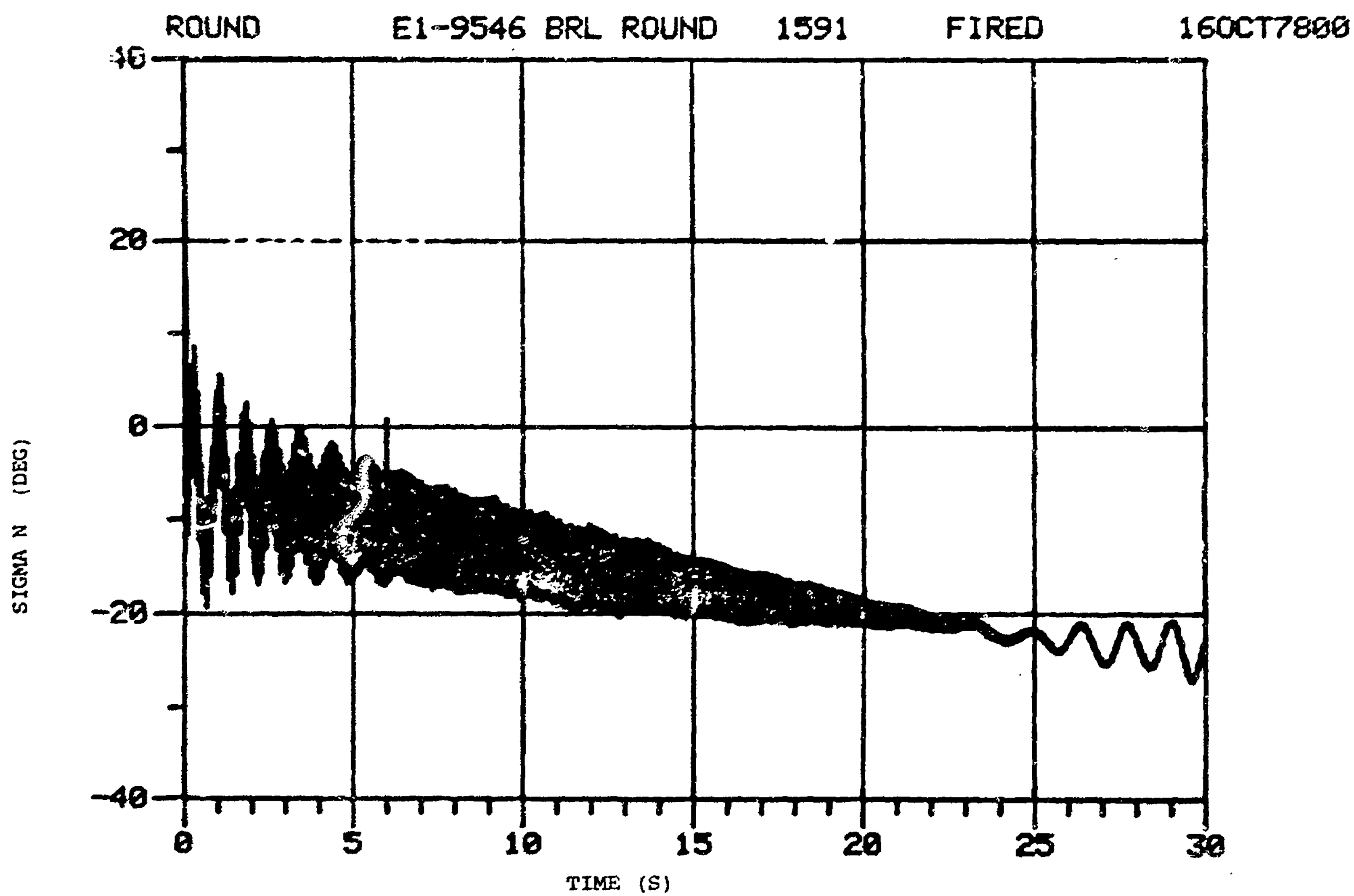

Figure 16. Sigma N versus Time for E1-9546.

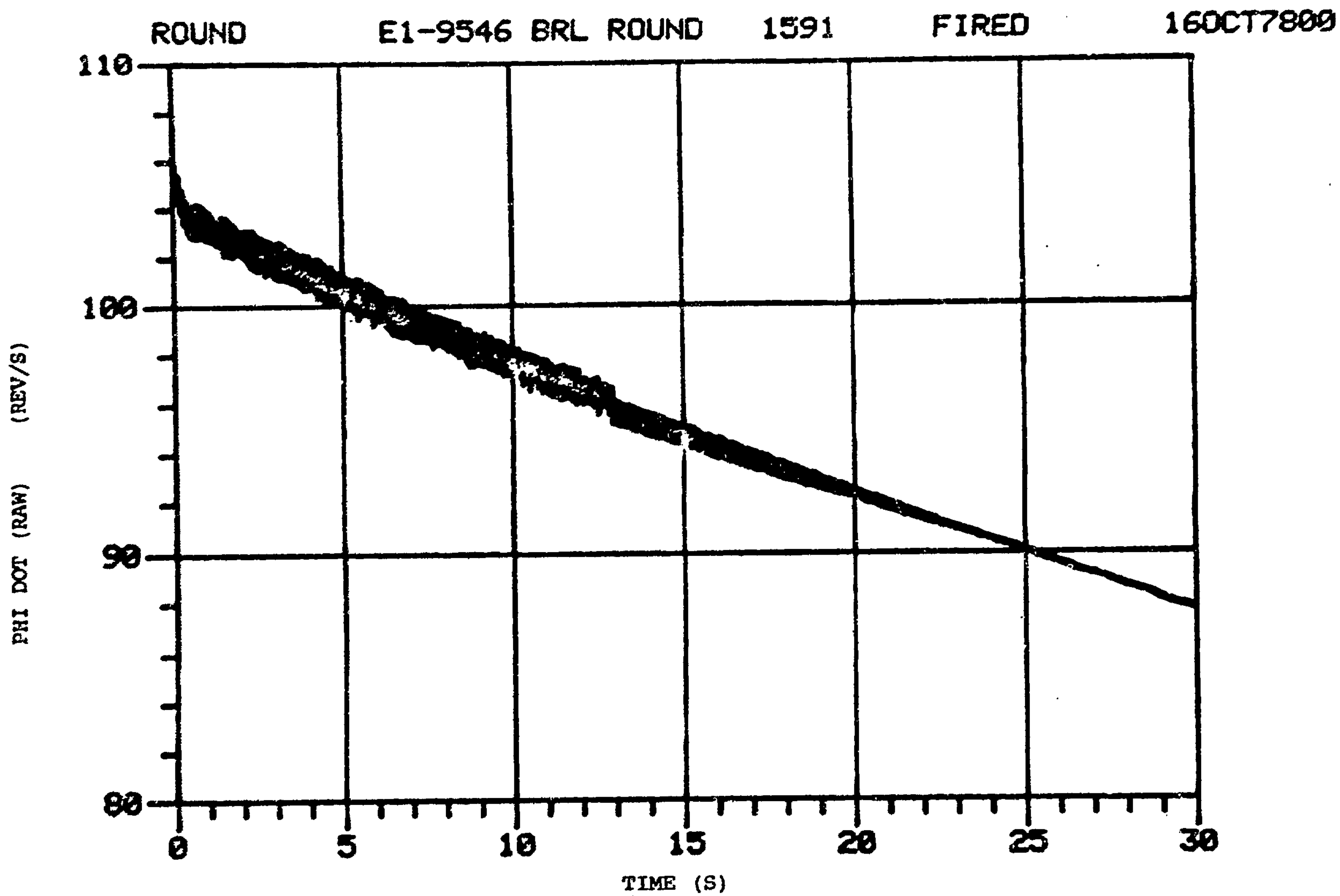

Figure 17. Phi Dot (Raw) versus Time for E1-9546.

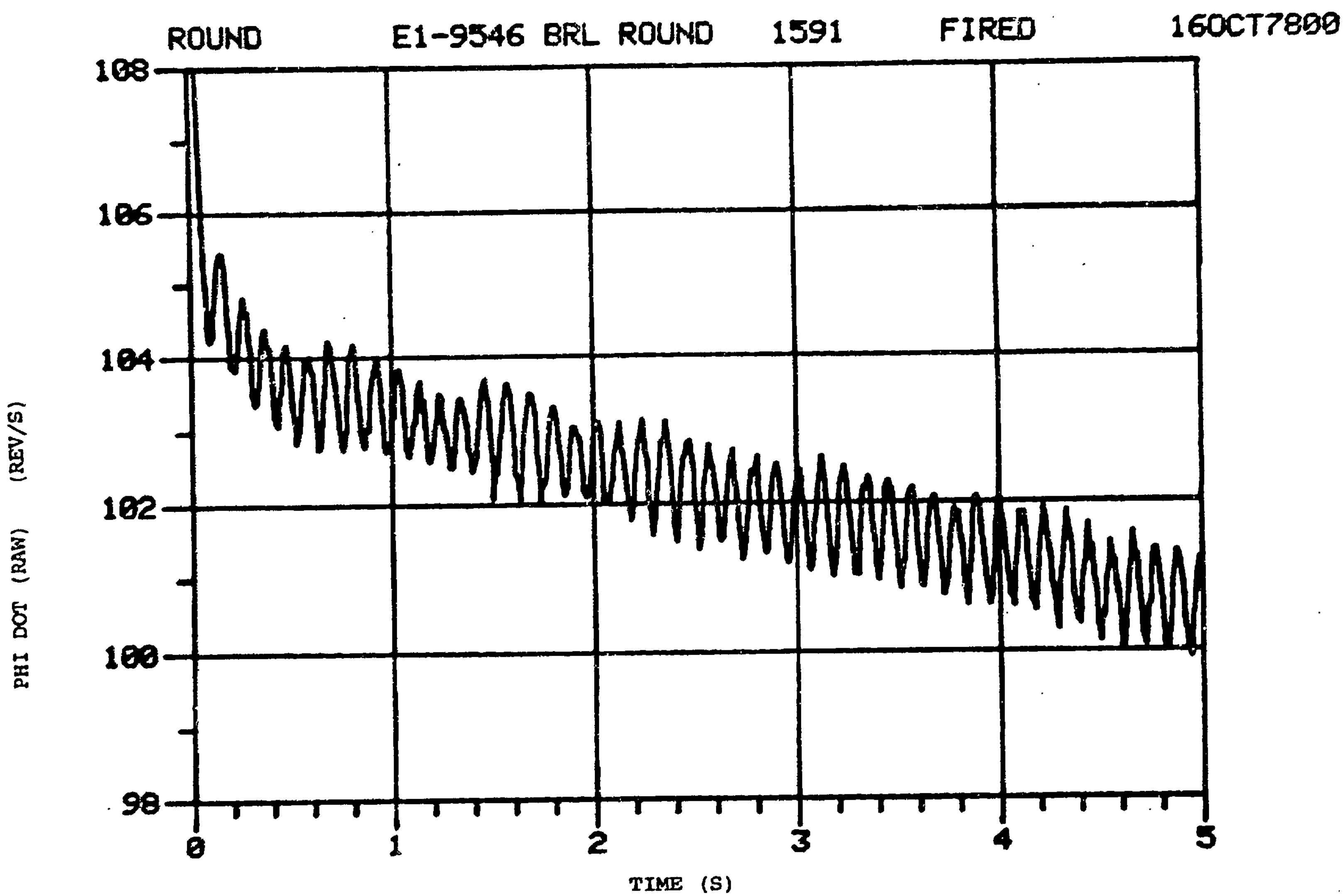

Figure 18. Phi Dot (Raw) versus Time for E1-9546 (Zero to 5s).

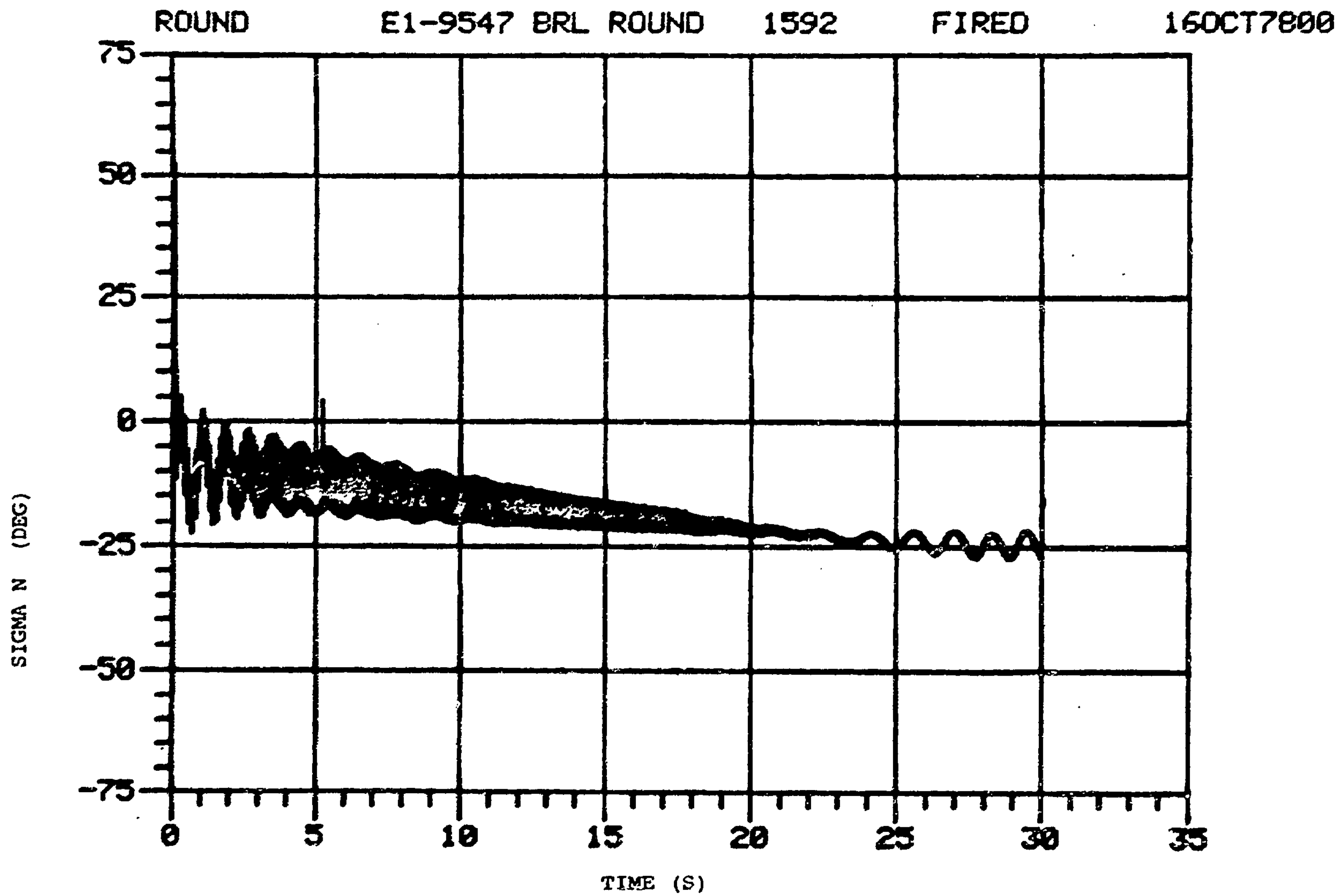

Figure 19. Sigma N versus Time for E1-9547.

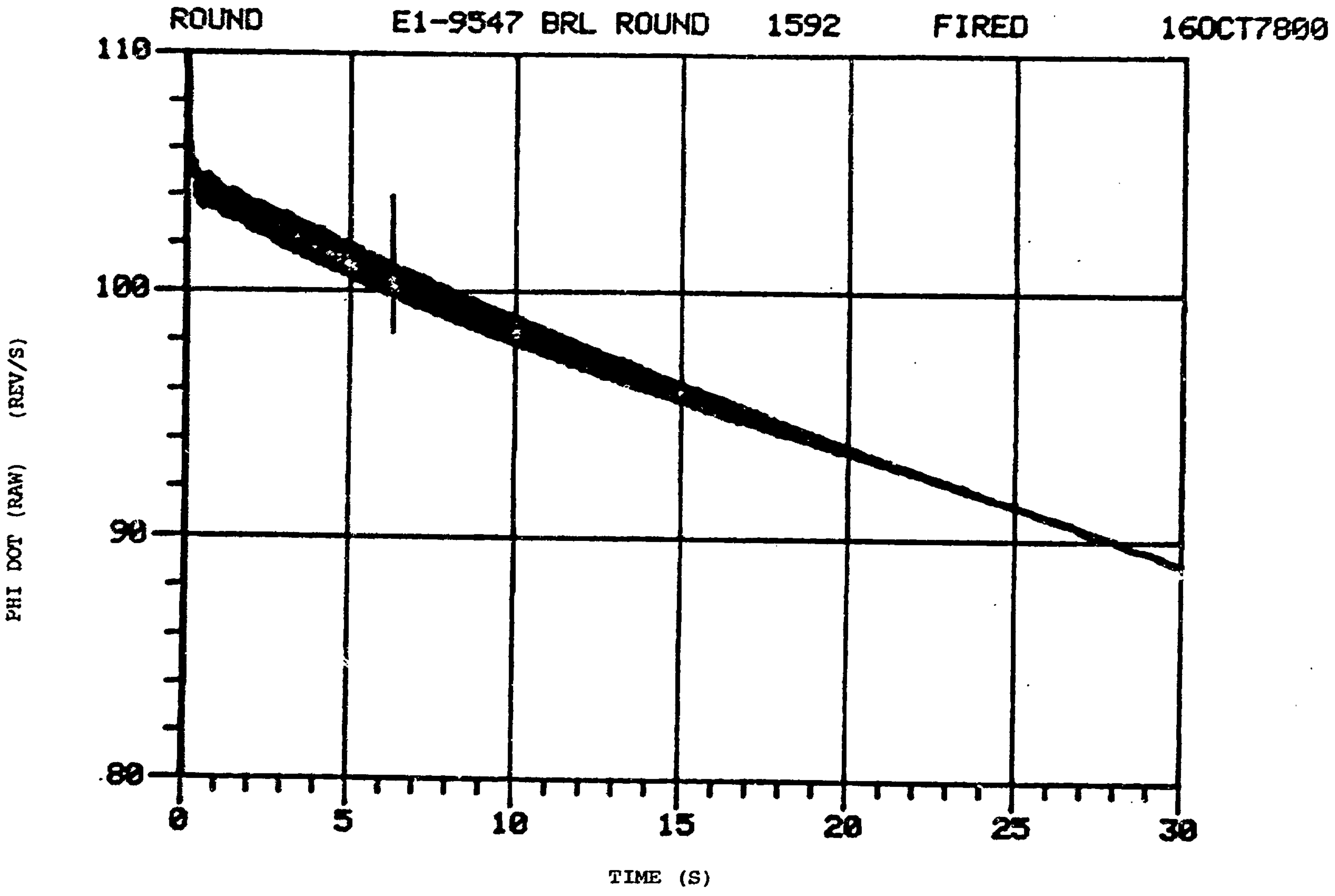

Figure 20. Phi Dot (Raw) versus Time for E1-9547.

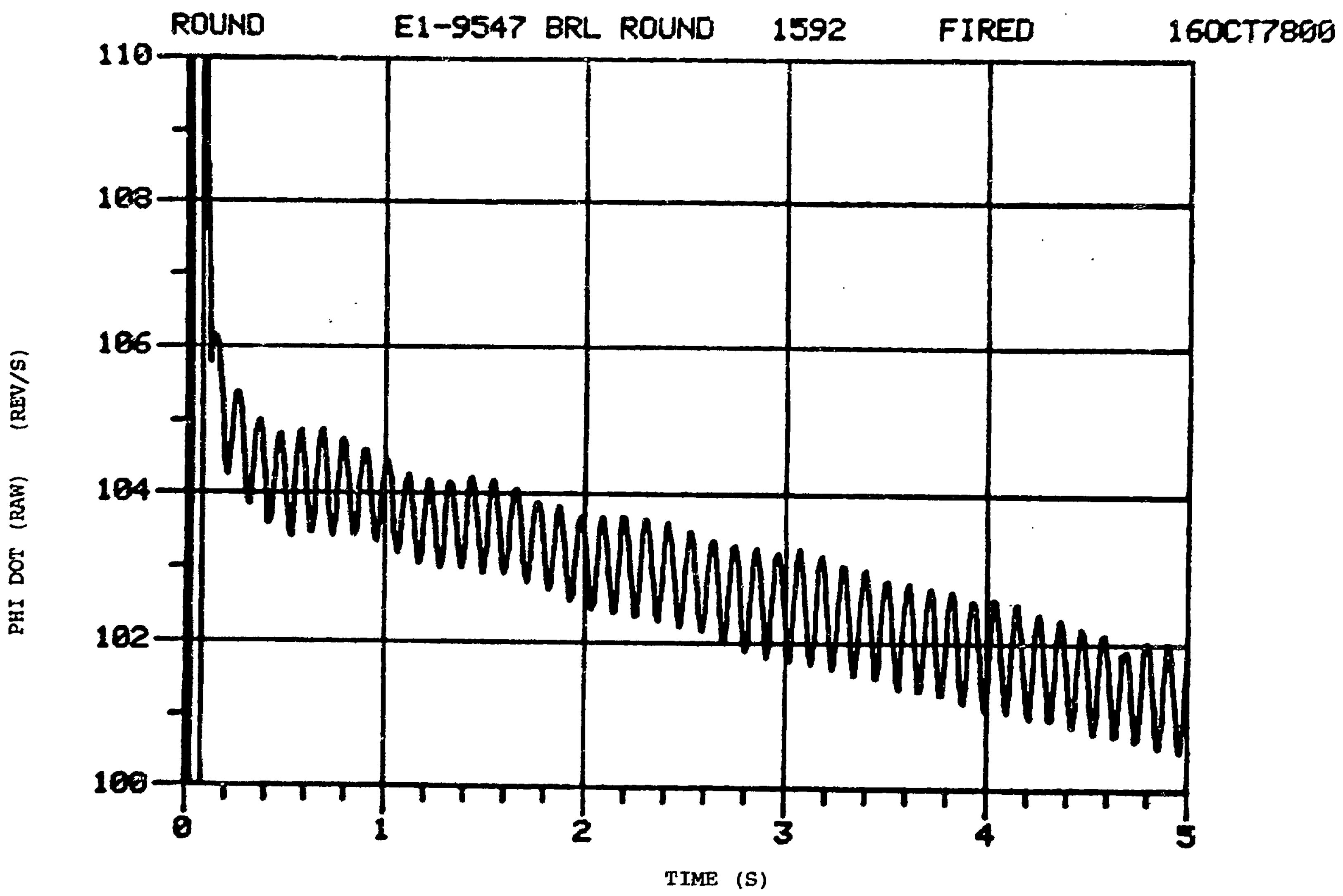

Figure 21. Phi Dot (Raw) versus Time for E1-9547 (Zero to 5s).

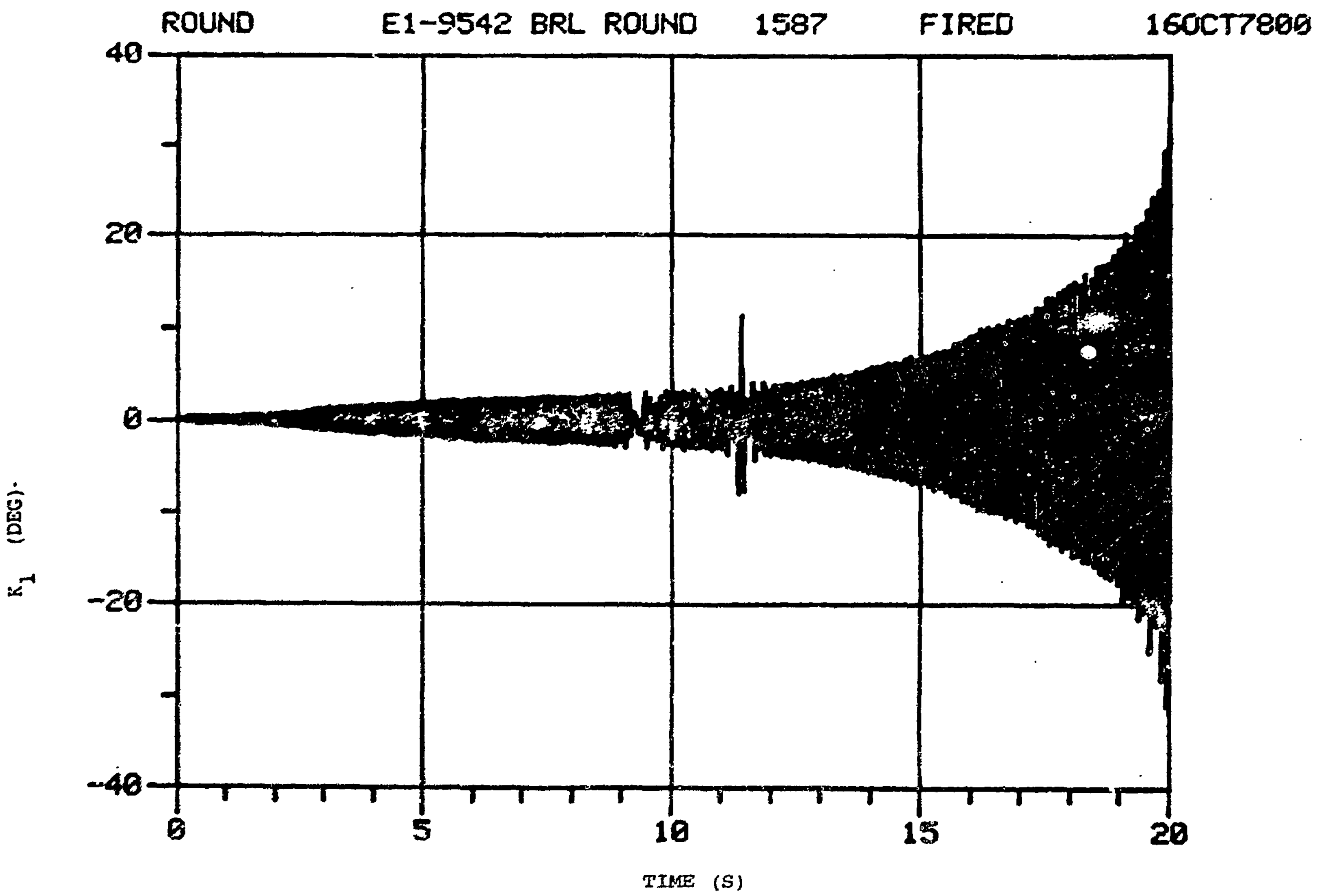

Figure 22. Fast Precessional Mode Envelope versus Time for E1-9542.

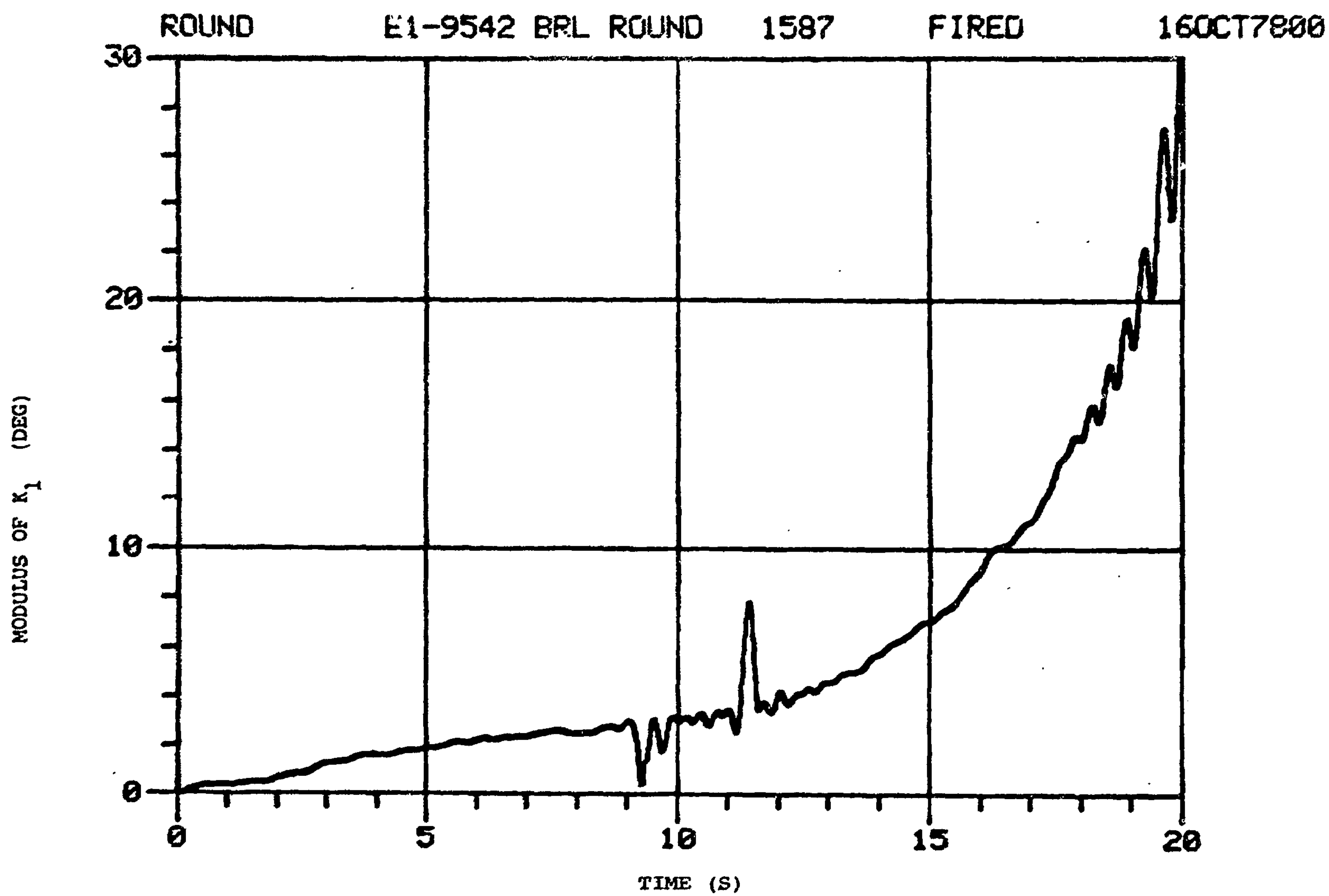

Figure 23. Fast Precessional Mode Amplitude versus Time for E1-9542.

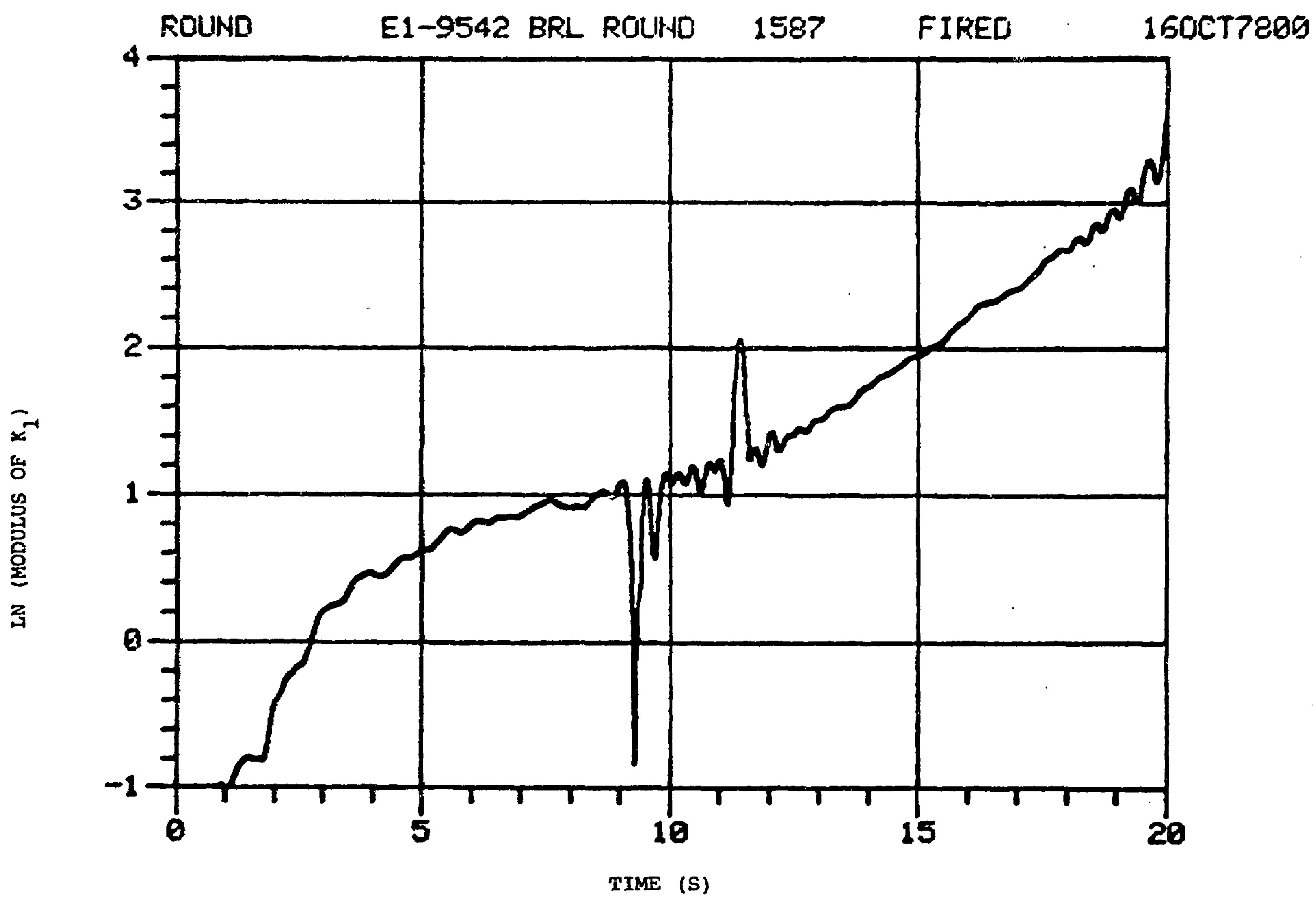

Figure 24. Log of Fast Precessional Mode Amplitude versus Time for E1-9542.

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